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A COMPARISON OF REWARMING METHODS IN MILDLY HYPOTHERMIC INDIVIDUALS

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The purpose of this study was to compare the rewarming effectiveness of a radio frequency coil (13.56 MHz) at a specific absorption rate (SAR) of 2.5 W/kg (RF) with warm water immersion (40°C) (WW) and an insulated mummy-type rewarming sack (TS). Four male subjects, ages 24-35, were immersed in 10°C water for up to 90 minutes or until their rectal temperatures (T_{re}) decreased to 35°C. Each subject had 3 trials in which they were immersed. After each immersion, rewarming was accomplished with either RF, WW, or TS, so that each subject was rewarmed once with each method. Comparisons of the three rewarming methods were based on the rate of increase of T_{re} during rewarming ($\Delta T_{re}/t$), T_{re} 60 minutes after the start of rewarming (T_{re60}), the time interval measured from extraction from the water to the end of afterdrop (Δt), and the magnitude of any observed T_{re} afterdrop (ΔT_{re}). WW had significantly greater $\Delta T_{re}/t$ and T_{re60} than either RF or TS ($p < 0.03$) and a smaller Δt than TS ($p < 0.05$). TS had significantly greater ΔT_{re} than either WW or RF ($p < 0.05$). No significant differences in $\Delta T_{re}/t$, T_{re60}, or Δt were observed between TS and RF. The results of this study indicate that for mildly hypothermic individuals, rewarming with RF at a SAR of 2.5 W/kg is roughly equivalent to TS and less effective than WW.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Present resuscitation methods for victims of accidental hypothermia are unsatisfactory for a number of reasons. Active internal rewarming measures such as cardiopulmonary bypass, mediastinal lavage, and hemodialysis, while effective, are highly invasive, require extensive equipment, and are not readily performed in a field or emergency room setting. The effectiveness of these methods results from their ability to warm internal organs with minimal skin surface heating (6,7). This minimizes the possibility of core temperature afterdrop which might otherwise occur by eliminating the temperature gradient between the core and skin surface during the early stages of rewarming (16,25). Active external methods such as warm bath immersion are also effective but limit access for patient care and place the patient at risk for core temperature afterdrop during the rewarming process. Passive rewarming while useful in the field, is a poor method for victims whose endogenous heat production is depressed due to lowered core temperature.

A major goal in hypothermia research has been the development of a field-usable rewarming method capable of noninvasive heating of deep body tissues. Radio frequency induction coils are an active noninvasive core rewarming technique, based on the principal of specific energy absorption by muscle and bone tissue, which hold the promise of minimizing afterdrop. As sudden deaths among ostensibly recovering hypothermia victims can often be attributed to core temperature afterdrop (6), this would be a significant contribution to field treatment. Rewarming of mammals has been reported with these coils (19,26), but development has been hampered by a proclivity for skin burns. Development by Olsen, et al (20) of a tunable radio-frequency induction coil has led to the successful rewarming of hypothermic rhesus monkeys. We report the testing of this device by rewarming mildly hypothermic human subjects. These results were compared with rewarming by two other methods: warm water immersion and a thermal rewarming sack.

MATERIALS AND METHODS

Subjects: Four males (Table 1), ages 24-35 years, volunteered to participate as subjects after being fully informed of the details of the experimental protocol and associated risks. These procedures were approved by the Naval Air Development Center's Advisory Committee for the Protection of Human Subjects and the Food and Drug Administration's Section for Investigational Medical Devices. Weight was recorded prior to each test run and the mean for each subject calculated. Body surface area (SA) was calculated (5) from the mean weight and height of each subject. Percent body fat was determined from estimates of body density (2), which were computed from skinfold measurements obtained with Lange Skinfold Calipers (Cambridge Scientific Inc., Cambridge, MD) and the equation of Lohman (23).

TABLE 1: Physical characteristics of subjects.

Subject	Sex	Age (yrs)	Height (m)	Weight (kg)	%Body Fat	Surface Area (m^2)
A	M	35	1.78	79.0	13	1.97
B	M	26	1.85	91.4	17	2.16
C	M	30	1.75	71.9	17	1.87
D	M	24	1.79	67.9	10	1.85
Overall mean		29	1.79	77.6	14	1.96
SEM		3	0.02	6.8	2	0.05

<u>Experimental Procedures</u>: Subjects reported to the laboratory and were given physical examinations by the attending flight surgeon. Urine samples were collected and analyzed as part of the flight surgeon's examination of the subject. Subjects wore a bathing suit, cotton tee shirt, 3/16" neoprene wet suit booties, anti-exposure mittens, a personal flotation device, and were instrumented with rectal and six surface skin temperature sensors. Booties and mittens were worn in an attempt to preclude trial terminations due to low extremity temperatures. Subjects were immersed to the neck in a stirred pool (1.5 m deep x 2.4 m diameter) of 10°C water until 90 minutes had elapsed, rectal temperature (T_{re}) = 35°C, hand or foot temperature (T_{hand}) = 10°C, heart rate (HR) exceeding 90% of the maximum predicted for age, or the subject, flight surgeon, or principal investigator requested removal of the subject. Following removal from the water, the flotation device, mittens, and booties were removed from the subject, who was then quickly dried with towels and rewarmed. The time from exiting the water to start of rewarming was 2.9 ± 1.0 minutes. Rewarming was by either the radio-frequency coil (RF), warm water immersion (WW), or a mummy-type thermal sack (TS). Subjects were transferred from the chamber to the rewarming area in a prone position and remained prone during rewarming except when repositioning rewarming devices. The experimental design counterbalanced the order of rewarming method and each subject acted as their own control. Trials for individual subjects were separated by at least 48 hours.

<u>Rewarming Methods</u>: Rewarming by each of the methods was continued until T_{re} = 37.0°C unless 60 minutes elapsed without a marked rise in T_{re}. When a negligible increase in T_{re} was observed after 60 minutes, rewarming using either RF or TS was terminated and the subject was rewarmed by WW.

Radio Frequency Rewarming Coil. The RF rewarming coil consisted of a helical coil of steel cable within a plastic sheath connected to a crystal oscillator (Electronic Navigational Instruments, Rochester, NY, model ACG-5) emitting radio frequency energy at 13.56 ± 0.01 MHz. The coil was kept away from the skin surface by four pads of Nautilux foam located about the torso. Specific absorption rates (SAR) were adjusted to 2.5 $W/kg_{body\ weight}$ by changing the output power of the coil for each subject (based on measured weight). The RF system was tuned for each subject during rewarming to minimize the amount of reflected power. A RF field density of 2.6 mW/cm^2 was measured at a distance of 1 meter from the RF coil during operation. During this study, the RF coil covered the subject's torso from just below the clavicle to approximately 10 cm below the level of the umbilicus. All metal was kept clear of the RF field during rewarming to prevent skin burns from RF resonant heating. Hot spots generated by variations in coil fit were identified by the subject and the coil adjusted accordingly.

Mummy-type Thermal Sack. The thermal sack (Domtex International, Yorkshire, UK, model Decupad Thermal Recovery Capsule) was a mummy-type bag with a high pile polypropylene lining. The lining was intended to provide thermal insulation and wick moisture from a hypothermia victim's clothing and skin. The bag completely covered an individual except for the face. Multiple zippers allowed access to all body areas during use.

Warm Water Immersion. Subjects were immersed in stirred 40°C water with their head and extremities out. When a positive trend was observed for the change in T_{re} lasting more than 10 minutes, subjects were permitted to place their extremities in the water.

Physiological Measurements: Use of RF energy precluded the use of thermocouple or thermistor temperature sensors during rewarming because of their metallic composition. To measure temperatures accurately during rewarming, a fibre optic temperature measurement system designed for use in RF fields was employed (Luxtron Corp., Mountain View, CA, model 3000). Dual sensors were inserted 8 cm past the anal sphincter for measuring T_{re} while surface skin temperatures were measured at 6 sites (i.e., forehead; arm (biceps), lateral surface of torso (approx. 4th intercostal space), upper chest, anterior thigh, and lower back. Thermistors were used for monitoring hand and foot temperatures during pre-rewarming immersions; as they could not be employed during RF rewarming, they were removed prior to initiating rewarming in all trials. Electrocardiograph (ECG) signals were monitored during pre-rewarming immersions with ECG electrodes (3M, Minneapolis, MN, Red Dot) amplified with isolated ECG amplifiers (Gould, Cleveland, Ohio, model 4600 series amplifiers). The ECG electrodes were also removed prior to the start of rewarming procedures. Cardiovascular status of subjects during WW and TS rewarming was monitored by means of a stethoscope; during RF rewarming a plastic stethoscope was used.

Subjective Responses: Subjective sensations were evaluated every 15 minutes throughout the exposure period by means of scales for fatigue, shivering, temperature, and comfort. Subjects were instructed to indicate their subjective sensation for each criterion on a 1 - 7 scale where 1 indicated the most pleasant situation and 7 the most unpleasant.

Calculated Values: Comparisons of the three rewarming methods were based on the rate of increase of T_{re} during rewarming ($\Delta T_{re}/t$), the time interval measured from extraction from the water to the end of afterdrop (Δt_{ad}), the magnitude of any observed T_{re} afterdrop (ΔT_{ad}), and T_{re} 60 minutes after the start of rewarming (T_{re60}). The $\Delta T_{re}/t$ was calculated from the slope of the T_{re} first order regression line divided by the duration of rewarming. The slope was calculated from the time a positive trend was observed in T_{re} following the start of rewarming procedures. The Δt_{ad} was calculated from the end of immersion to the beginning of a monotonic increase in T_{re} (i.e., the 'afterdrop phase'). The ΔT_{ad} was determined by subtracting the nadir of T_{re} during the 'afterdrop phase' from the T_{re} observed at the end of immersion. T_{re60} was determined from the moment rewarming procedures began. Values of T_{re60} were linearly extrapolated if rewarming did not last 60 minutes.

The energy transfer efficiency of the RF was determined by estimating the power required to raise T_{re} the amount observed in each of the RF runs. This was given by:

(1) $P_{RW} = (0.83)(M_b)(\Delta T_{rw})(1000)(.001164)/(t)$ (Watts)

where P_{RW} = power needed to rewarm subject, M_b = body mass (kg), ΔT_{rw} = T_{re} increase during rewarming (°C), t = rewarming time in hours, 0.83 = body specific heat (cal g^{-1} °C^{-1}), 1000 and .001164 = conversion factors (g kg^{-1}) and (W hr cal^{-1})) respectively. It was assumed for these calculations that there was no metabolic contribution to P_{rw}, i.e., metabolic heat production was balanced by heat losses to the environment. The power output of the RF coil was calculated from:

(2) $P_{RF} = (SAR)(M_b)$ (Watts).

It was assumed for this calculation that there were negligible losses from reflection. As the coil was tuned for individual subjects during rewarming, actual losses due to reflection were generally < 10%. Efficiency was then determined by:

(3) Efficiency = $P_{RW}/P_{RF} \times 100$ (%).

Statistical Analysis: Physiological data from this study was analyzed using the non-parametric Friedman Analysis of Variance (ANOVA). When significance was detected, the Mann-Whitney U test was used to identify where the differences existed between rewarming methods. The non-parametric Kruskal-Wallis ANOVA was used to detect differences in subjective responses (as a function of time) between rewarming methods. Regression analysis was used to determine the slopes of the rewarming T_{re} first order regression lines. Missing initial values were estimated by the technique of Winer (27). Differences were considered significant at the level of $p<0.05$.

RESULTS

Induction of Mild Hypothermia: The immersions prior to rewarming had a mean duration of 73.5 ± 19.7 minutes. Within this time, a mean ΔT_{ad} = -1.7 ± 0.7 °C was observed, with a mean final T_{re} prior to rewarming = 35.8 ± 0.8 °C. While the final T_{re}'s were higher than desired (i.e., T_{re} = 35.0 °C), they were found to be significantly lower than the initial T_{re} ($p<0.001$). Individual skin site temperatures at the end of immersion ranged from T_{thigh} = 10.2 ± 0.5 °C to $T_{forehead}$ = 32.8 ± 1.0 °C while mean final heart rate (HR) = 100 ± 14 beats/minute (bpm). No significant differences between rewarming methods were observed for any of these parameters during induction of mild hypothermia. A typical subject's T_{re} data over the duration of his three trials is given in Figure 1.

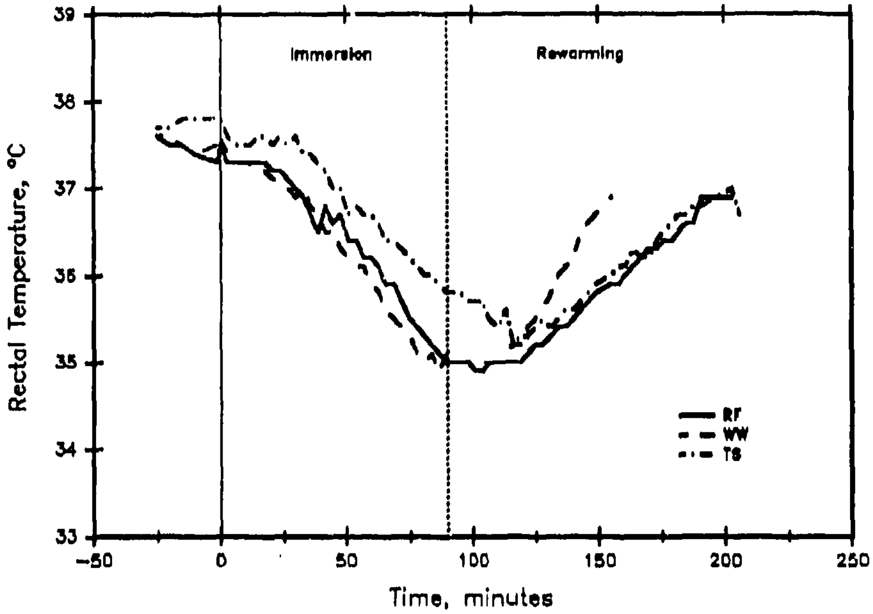

Figure 1. Rectal temperatures during cooling and rewarming for one subject. The period prior to immersion was the preparation time spent in the laboratory.

Rewarming:

Rate of increase of T_{re} during rewarming: Mean $\Delta T_{re}/t$ for the rewarming methods are given in Figure 2. Warm water rewarming (WW) resulted in a significantly larger $\Delta T_{re}/t$ than either the RF coil (RF) ($p < 0.03$) or the thermal sack (TS) ($p < 0.03$). No significant difference was observed between the RF and TS. These results are shown in the regression lines generated for each method given in Figure 3.

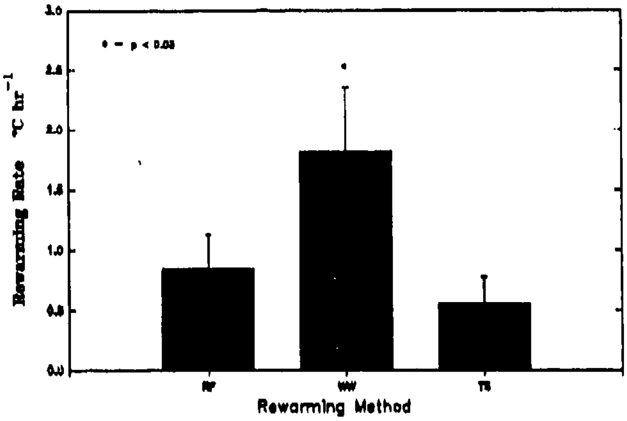

Figure 2. Rewarming rates determined from the start of a monotonic increase in rectal temperature. Values are means ± SEM, n = 4.

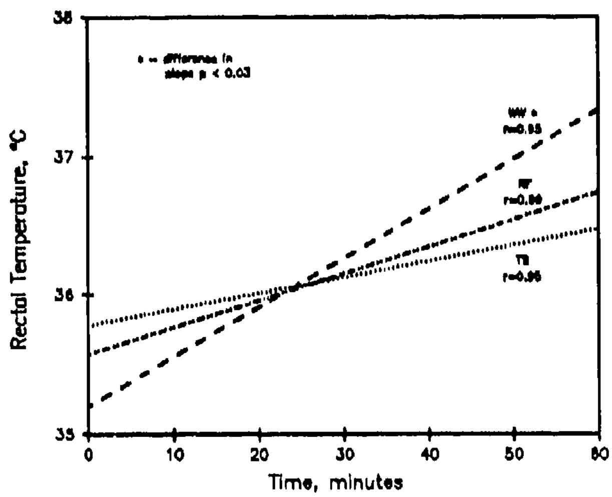

Figure 3. First order regression lines for rectal temperature during rewarming. The starting point for the calculations was the initiation of a monotonic increase in rectal temperature following any afterdrop which had occurred. (n = 4 for each method)

Duration and magnitude of rectal temperature afterdrop: A significantly shorter Δt_{ad} was observed during the WW trials compared with the TS trials ($p < 0.05$). No other significant differences in Δt_{ad} were noted between the rewarming methods. ΔT_{ad} was significantly larger in the TS trials compared with WW ($p < 0.05$) and RF ($p < 0.03$) trials. The differences in ΔT_{ad} between RF and WW trials were not observed to be significant. Mean values of Δt_{ad} and ΔT_{ad} are given in Figure 4 and 5, respectively.

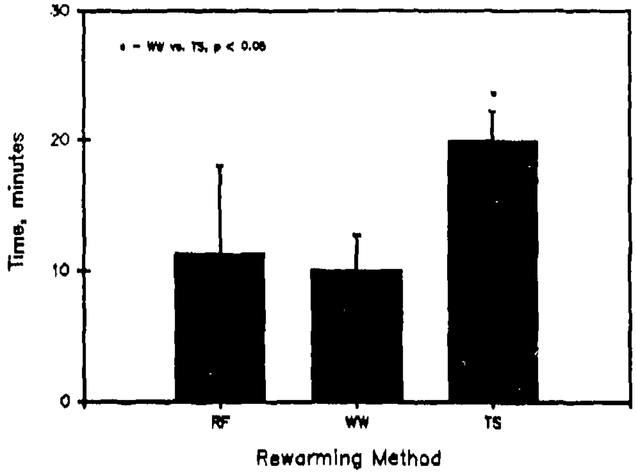

Figure 4. Duration of afterdrop by rewarming method. Values are means ± SEM, n = 4.

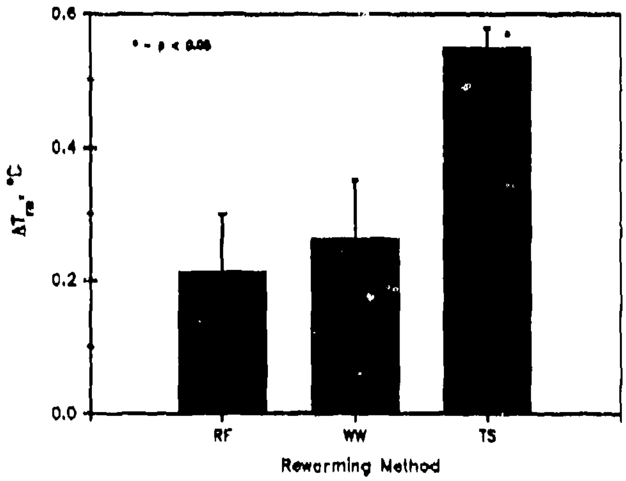

Figure 5. Magnitude of afterdrop by rewarming method. Values are means ± SEM, n = 4.

Rectal temperature after 60 minutes: A significantly greater $T_{re,60rw}$ was observed for WW than either RF or TS ($p < 0.01$). Mean $T_{re,60rw}$ are given in Figure 6.

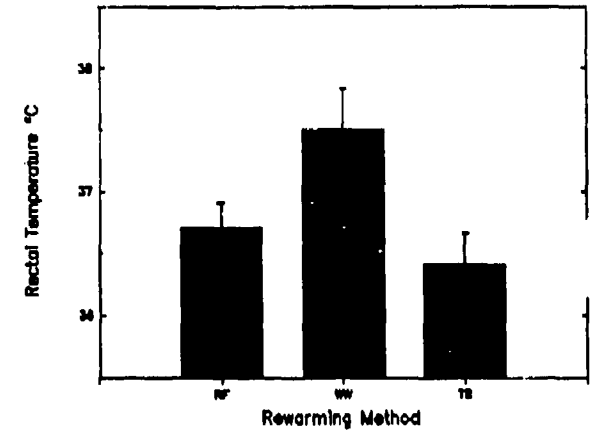

Figure 6. Rectal temperatures 60 minutes after the initiation of rewarming.Values are means ± SEM, n = 4 for RF and TS. Three of 4 values given for WW are extrapolated, as the WW rewarming phase lasted < 60 minutes.

Heart rate: No significant differences between methods were observed for heart rate during the rewarming trials. Regression lines of mean HR for each rewarming method are given in Figure 7. These findings indicate that there was no significant difference in physiological stress during rewarming with either RF, WW, or TS.

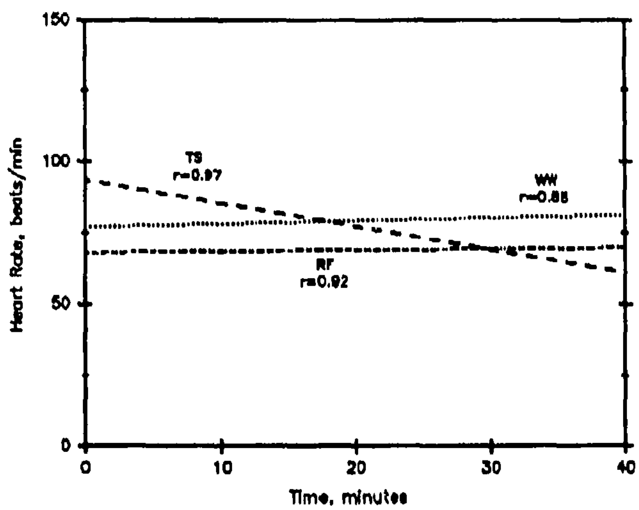

Figure 7. First order regression lines for heart rate during rewarming (n = 4 for each method).

Skin temperatures: As expected, WW rewarming resulted in significantly higher skin temperatures throughout most of rewarming ($p<0.01$) compared with RF and TS. Figures 8 and 9 show this to be true even for back and chest temperatures, which together represent the part of the body (i.e., torso) where the RF deposited most of its energy. No significant differences in skin temperatures were noted between RF and TS.

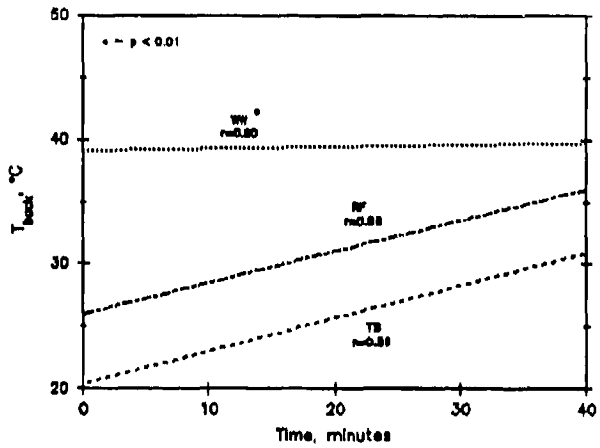

Figure 8. First order regression lines for back temperature during rewarming (n = 4 for each method).

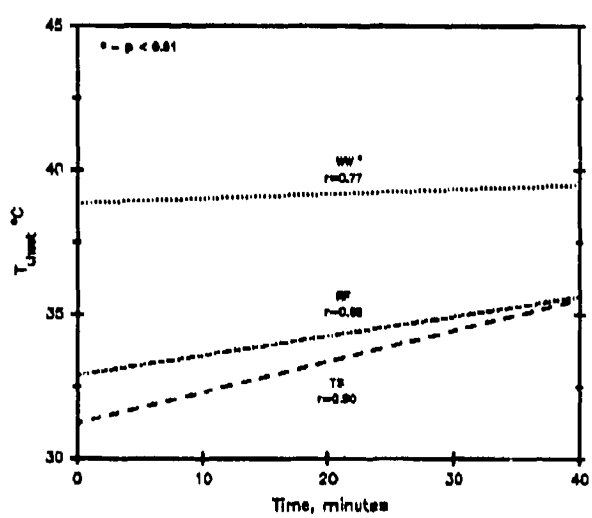

Figure 9. First order regression lines for chest temperature during rewarming (n = 4 for each method).

Subjective responses: No significant differences were observed between rewarming methods for any of the subjective measures recorded in this study. Differences in subjective responses between subjects were also not significant during rewarming. This data indicates that no distinction could be made between rewarming methods on the basis of subjective tolerance.

RF efficiency: The lower the eff:ciency the less effective RF will be for rewarming hypothermic individuals. The mean efficiency of the RF coil -

32 ± 11%. An important factor in the observed variability in efficiency was the difference in ability to tune the coil for individual subjects. In addition, while the RF coil had a focused field, there were stray losses to the surroundings which contribute to lowered efficiency. Stray losses, however, should be similar between runs.

RF efficiency: The lower the efficiency the less effective RF will be for rewarming hypothermic individuals. The mean efficiency of the RF coil = 32 ± 11%. An important factor in the observed variability in efficiency was the difference in ability to tune the coil for individual subjects. In addition, while the RF coil had a focused field, there were stray losses to the surroundings which contribute to lowered efficiency. Stray losses, however, should be similar between runs.

DISCUSSION

Active rewarming of the body core exclusively is generally considered the theoretical ideal for treating accidental hypothermia. This would avoid vasodilation of cooled extremities (which would result in return of cooled blood to the body core) and minimize core/skin temperature gradients, eliminating the two postulated causes of core temperature afterdrop. Passive rewarming (assisting endogenous heat production by eliminating heat loss) is only applicable at core temperatures of 32°C and above and presumes underlying good health (6).

Certain complexities of rewarming research have frustrated successful identification of rewarming methods that approach the ideal. These typically stem from three variables encountered in hypothermia research: 1) methods of core temperature assessment (rectal, esophageal, tympanic); 2) final endpoints for induction of hypothermia (35°C or pre-established decreases in core temperature), and 3) the choice of a rewarming method for use as an experimental control.

Radio frequency rewarming techniques appear to have promise as a field-usable method providing primarily central rewarming. Final conclusions on its effectiveness are frustrated, however, by variable assessment techniques. A previous study by Hesslink, et al (10) reported this active, non-invasive rewarming method to be superior to warm water immersion. An exploration of the confounding variables between the present work and that of Hesslink, et al (10) demonstrate the difficulty associated with drawing a final conclusion on RF.

First, it has been argued by a number of authors (1,9,21) that esophageal temperature (T_{es}) is more representative of core temperature, i.e., the temperature of the right atrium (T_{ra}), than other possible body sites. Assuming this to be true and coupled with the knowledge that the RF coil deposits a considerable proportion of its energy in the thoracic region, T_{es} ought to be more sensitive to changes brought about by warming due to RF energy than T_{re}. However, measurement of T_{es} was not possible in the present study. While use of T_{re} may not have provided as good an absolute measure of rewarming effectiveness of WW, RF, or TS, the relative effectiveness should still be easily discerned. This conclusion is based on comparative studies utilizing both T_{es} and T_{re} (8,11,21,22). In these studies, the more effective rewarming techniques were apparent from both T_{es} and T_{re} data, with the relative ranking of methods constant with either temperature measure.

In fact, the rapid response of T_{es} compared with T_{re} observed in the Hesslink, et al. study (10) may represent the fact that the mass of the body was not deeply cooled. Mittleman and Mekjavic (16) demonstrated that T_{es} is influenced by peripheral blood temperatures while T_{re} is not. Thus the relatively warm triceps temperatures observed by Hesslink, et al (10) suggest that the peripheral blood supply enhanced the observed T_{es} rebound. As T_{re} is dependent upon convective heat exchange from the central blood supply and conductive heat exchange with surrounding tissues, then relatively warm peripheral tissues at the start of rewarming would selectively aid the increase in T_{es} independent of other factors without directly influencing T_{re}.

Second, differences exist with the final endpoints for hypothermia induction. Hesslink, et al (10) terminated their cooling phase after a $\Delta T_{re} = -0.5°C$, which represents a very mild temperature excursion. Skin temperatures reported in that study during the cooling phase are also quite warm relative to the water temperature, and further suggest only slight body cooling. The quasi-steady state temperature losses observed in longer duration cold exposures (12,13,24) had apparently not been achieved. Based on the temperature data from the present study and other reported unprotected exposures (12,24), the immersion times reported by Hesslink, et al. (10) (i.e., means of 32-37 minutes) appear too short in 11°C water to achieve thermal balances corresponding to mild hypothermia.

As discussed above, this low level of cooling could have significantly influenced their rewarming results. Furthermore, the afterdrop observed with WW and TS by Hesslink, et al. (10) probably represent primarily conductive heat transfer as suggested by Webb (25). This is suggested by the warm skin temperatures which would eliminate a source of cool peripheral blood to be returned to the core. As lower extremity temperatures were not measured, one cannot be certain of overall peripheral blood temperatures. The relatively warm back temperatures, however, suggest that lower extremity temperatures that study were relatively high (10). This also suggests that without skin temperature data from the cooling period, it is difficult to evaluate the claim of Romet (21) that conductive heat transfer is a primary source of afterdrop when T_{sk} is not brought above 33°C during rewarming. It therefore seems obvious that studies attempting to assess the relationship of afterdrop to rewarming processes bring core and skin temperatures as low as ethically possible.

The present study brought T_{re} and the various skin temperatures to levels clearly representative of mild hypothermia. As such, it is felt that the elicited responses more accurately represent the rewarming capabilities of the assorted rewarming techniques. Of particular significance is the rather large temperature gradients during WW resulting from the low temperatures achieved during cooling; this would have provided the driving force allowing significant heat transfer across the skin surface during WW rewarming. RF and TS would have been less efficient with low skin surface temperatures. RF deposits upwards of 25% of the transmitted energy at the body surface; initial skin warming may have elicited vasodilation thereby increasing body heat losses to the relatively cool surroundings. Also, with a relatively cold surface, much of the deeply deposited RF energy would have be convected outward, further reducing the effectiveness of the device to heat the body core. Similarly, a cold skin surface would have reduced the percentage of generated metabolic heat available for heating the body core during the use of the TS, as some of it would have been transferred to the cooler periphery.

Inconsistencies are also seen between the present study and that of Hesslink, et al (10) with regard to the effectiveness of WW. The T_{re} rewarming rate for WW of 1.8°C/h observed in this study is similar to those found in other WW studies by Romet (21) of 1.6°C/h and Hoskin, et al. (11) of 2.3°C/h. While Hoskin, et al (11) began rewarming after a pre-rewarming ΔT_{re} of 1.6°C, which is similar to the pre-rewarming ΔT_{re} = 1.9°C in the present study, Romet (21) only had a pre-rewarming ΔT_{re} of 0.5°C prior to rewarming. Curiously, the data of Hesslink, et al. (10) indicate an overall T_{re} rewarming rate of 0.3°C/h for WW despite a ΔT_{re} of 0.5°C prior to rewarming, a pre-rewarming ΔT_{re} identical to that of Romet (21). These anomalous results may be due to the position in the tub during rewarming, i.e., Hesslink, et al. (10) kept the upper chest and neck out of the water in contrast to the other studies which immersed people up to the neck. Clearly, for rewarming results to be compared, the techniques used must be similar.

From a theoretical standpoint, RF should provide a superior means of increasing T_{re} while minimizing afterdrop compared to either WW or TS (7,10,20,26) based on the RF's method of operation. This was not observed in this study based on the $\Delta T_{re}/t$, Δt_{ad}, and ΔT_{ad} results. It is believed that the factors contributing to these results include: a) energy absorption by the skin, subcutaneous tissues, surface moisture, and the plywood tabletop on which subjects lay; b) lack of insulation between the skin surface and the ambient environment, allowing heat losses across the skin surface; and c) a lower SAR than required to quickly rewarm mildly hypothermic humans.

The relatively low efficiency in transferring RF energy to the body can be attributed to a number of factors. The most obvious is losses due to reflected power, although careful tuning limited losses to less than 10%. Surface absorption is known to occur with RF energy (4,19) with upwards of 25% of the energy being deposited there (R. Olsen, personal communication). Water remaining on the skin surface was also recognized as a potential energy sink. In an attempt to address this problem, the protocol required that subjects were dryed off with a towel immediately prior to rewarming. While this was generally successful in removing excess water, there is no doubt that some water was retained which would have reduced the efficiency of the RF.

Energy absorption by the plywood table used for rewarming has also been suggested as a potential cause of RF energy losses. This was unanticipated during the planning and execution of this study, but the resins used in plywood construction apparently have the potential for absorbing RF at 13.56 MHz. This does not appear to be a significant factor, however, since RF absorption would result in heating of the plywood. No appreciable warming of the plywood was noted during the study.

The lack of insulation between the skin surface and the ambient environment during RF rewarming would have resulted in continued heat losses. While the skin temperatures increased during RF, the temperature gradient between the skin and environment would also increase. Increasing skin temperatures would have precluded vasoconstriction, eliminating the only means available to minimize trans-skin heat losses under the study conditions. This was not a problem with either TS or WW rewarming. WW utilized the thermal gradient between skin and water to transfer heat to the body, while the insulation of TS minimizes heat transfer between the skin and ambient environment. Future work with the RF coil should include insulation of the skin surface, so that this source of heat loss is mitigated.

The $\Delta T_{re}/t$ for RF of 0.8°C/h observed in the present study, at a mean rewarming starting T_{re} = 35.9°C, compares unfavorably with earlier work with RF coils. Rhesus monkeys, when initially cooled to T_{re} = 28.3°C, demonstrated $\Delta T_{re}/t$ of 5.6°C/h at a SAR of 5.5 W/kg_{body} (18) while hypothermic dogs, cooled to a tympanic temperature (T_{ty}) of 25°C, had a $\Delta T_{ty}/t$ of 5.2°C/h, at SARs of 4-6 W/kg_{body} (26). This suggests that an increased SAR would probably increase $\Delta T_{re}/t$. Morrison et al. (17) stated, however, that the rewarming rate may be dependent on initial core temperature at the start of rewarming. If this is the case, then any assumption of a linear relationship between SAR and rewarming rate appears ill advised. This premise is supported by comparing the $\Delta T_{re}/t$ data from the present study with that of Hesslink, et al. (10). Subjects in that study (10), with a pre-rewarming ΔT_{re} = 0.5°C, had an overall T_{re} rewarming rate of 0.3°C/h for RF rewarming. It should be noted that contrary to the method used to determine $\Delta T_{re}/t$ in that study (10), the rate reported here was determined from the ΔT_{re} over the entire rewarming period, a method consistent with other rewarming studies.

Morrison, et al. (17) determined his T_{re} dependence based upon inhalation rewarming data, which transfers much smaller quantities of heat to the body than RF (15). The relatively low efficiency of the RF coil in this study, resulting in a smaller energy transfer than anticipated, suggests that the conclusions of Morrison, et al. (17) may be appropriate for the present conditions. Interestingly, the animal RF studies cited (18,26) produced greater $\Delta T_{re}/t$ than a study employing an esophageal thermal tube (14), in which a $\Delta T_{re}/t$ = 4.0°C/h was observed with dogs cooled to T_{re} = 23.3°C. Since the esophageal thermal tube clearly rewarms centrally, the RF animal studies indicate the potential for central rewarming by RF.

A number of practical considerations must also be addressed if RF is to become a useful field rewarming method. Radio frequency interference with ECG signals precluded this type of cardiac monitoring during the present study. This would be unacceptable when dealing with cases of severe hypothermia. Identification of local hot spots and adjustments to the coil to avoid skin burns was dependent upon an alert and cooperative subject. For field use, a more dependable method of skin temperature monitoring would be required. In addition, adjustments to the coil could be difficult or hazardous with an unconscious or injured hypothermia victim. These deficiencies can possibly be corrected with further development, but they must be borne in mind when discussing an RF rewarming coil as a potential field device.

This study demonstrated the effectiveness of WW rewarming as a means of quickly raising T_{re} in mildly hypothermic individuals. Afterdrop during WW rewarming was not as dramatic as suggested in earlier literature (3,8,9,10). Its simplicity and effectiveness support continued use of WW as a method of choice for rapid rewarming of hypothermic individuals under the test conditions. RF and TS proved to be roughly equivalent in the ability to rapidly increase T_{re}, though use of TS was observed to produce a greater afterdrop. Both RF or TS were observed to be significantly less successful in rapidly increasing T_{re} during rewarming than WW.

In conclusion, WW rewarming was observed to be the most effective means of rewarming mildly hypothermic individuals when compared with RF or TS. While RF was shown to be at least as effective as TS, the low efficiency of energy transfer, along with other factors impeding energy deposition within the core tissues, hampered its performance. While the RF rewarming method continues to holds promise as a small and effective field-usable device, considerable work has yet to be done to demonstrate performance on par with WW. In future studies of these and other rewarming techniques, attention should be paid to establishing protocols which accurately demonstrate rewarming capabilities. To accomplish this, subjects need to be sufficiently cooled so that mild hypothermia is truly achieved. Core temperature should be evaluated by both Tre and Tes to permit evaluation of the various factors impacting the body 'core' (17). In addition, skin temperatures should be measured at sufficient sites to allow interpretation of surface temperature effects on the rewarming process during both cooling and rewarming.

CONCLUSIONS

1) Warm water (40°C) immersion was the most effective means of rewarming mildly hypothermic subjects in this study.

2) Use of the radio-frequency coil was at least as effective as the thermal sack for rewarming mildly hypothermic subjects.

3) The relative effectiveness of rewarming methods is dependent, in part, upon the extent to which hypothermia is induced in subjects.

4) Further development of the RF coil is necessary before it can be considered for field use.

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REFERENCES:

1. Brengelmann GL. Dilemma of body temperature measurement. In: Shiraki K and Yousef MK, eds. Man in Stressful Environments: Thermal and Work Physiology. Springfield, IL: Charles C Thomas: 1987, p. 5-23.

2. Brozek J, Grande F, Anderson JT, and Keys A. Densiometric analyses of body composition: revision of some quantitative assumptions. Ann. NY Acad. Sci. 1963; 110:113-140.

3. Collis ML, Steinman AM, and Chaney RD. Accidental hypothermia: An experimental study of practical rewarming methods. Aviat. Space Environ. Med. 1977; 48:625-632.

4. D'Andrea JA, Emmerson RY, DeWitt JR, and Gandhi OP. Absorption of microwave radiation by the anesthetized rat: Electromagnetic and thermal hotspots in body and tail. Bioelectromagnetics 1987; 8:385-396.

5. DuBois EF and DuBois D. Measurement of surface area of man. Arch. Int. Med. 1915; 15:868.

6. Harnett RM, Pruitt JR, and Sias FR. A review of the literature concerning resuscitation from hypothermia: Part I - The problem and general approaches. Aviat. Space Environ. Med. 1983; 54:425-434.

7. Harnett RM, Pruitt JR, and Sias FR. A review of the literature concerning resuscitation from hypothermia: Part II - Selected rewarming protocols. Aviat. Space Environ. Med. 1983; 54:487-495.

8. Hayward JS and Steinman AM. Accidental hypothermia: An experimental study of inhalation rewarming. Aviat. Space Environ. Med. 1975; 46:1236-1240.

9. Hayward JS, Eckerson JD, and Kenma D. Thermal and cardiovascular changes during three methods of resuscitation from mild hypothermia. Resuscitation 1984; 11:21-33.

10. Hesslink RL, Jr., Pepper S, Olsen RG, Lewis SB, and Homer LD. Radio frequency (13.56 MHz) energy enhances recovery from mild hypothermia. J. Appl. Physiol. 1989; 67:1208-1212.

11. Hoskin RW, Melinyshyn MJ, Romet TT, and Goode RC. Bath rewarming from immersion hypothermia. J. Appl. Physiol. 1986; 61:1518-1522.

12. Kaufman JW, Dejneka KY, Bagian JP, Morrissey SJ, and Bittner AC, Jr. Cold water evaluation of NASA Launch Entry Suit (LES). Naval Air Development Center, Warminster, PA, Tech. Rept. NADC-88-60-017, July, 1988.

13. Kaufman JW and Dejneka KY. Cold water evaluation of constant-wear anti-exposure suit systems.Naval Air Development Center, Warminster, PA, Tech. Rept. NADC-85092-60, June, 1985.

14. Kristensen G, Gravesen H, Benveniste D, and Jordening H. An oeosphageal thermal tube for rewarming in hypothermia. Acta Anaesth. Scand. 1985; 29:846-848.

15. Marcus P. Laboratory comparison of techniques for rewarming hypothermic casualties. Aviat. Space Environ. Med. 1978; 49:692-697.

16. Mittleman KD and Mekjavic IB. Effect of occluded venous return on core temperature during cold water immersion. J. Appl Physiol. 1988; 65:2709-2713.

17. Morrison JB, Conn ML, and Hayward JS. Accidental hypothermia: The effect of initial body temperatures and physique on the rate of rewarming. Aviat. Space Environ. Med. 1980; 51:1095-1099.

18. Olsen RG and David TD. Hypothermia and electromagnetic rewarming in the rhesus monkey. Aviat. Space Environ. Med. 1984; 55:1111-1117.

19. Olsen RG, Ballinger MB, David TD, and Lotz WG. Rewarming of the hypothermic rhesus monkey with electromagnetic radiation. Bioelectromagnetics 1987; 8:183-193.

20. Olsen RG. Reduced temperature afterdrop in rhesus monkeys with radio frequency rewarming. Aviat. Space Environ. Med. 1988; 59:78-80.

21. Romet TT. Mechanism of afterdrop after cold water immersion. J. Appl. Physiol. 1988; 65:1535-1538.

22. Romet TT and Hoskin RW. Temperature and metabolic responses to inhalation and bath rewarming protocols. Aviat. Space Environ. Med. 1988; 59:630-634.

23. Sinning WE, Dolny DG, Little KD, Cunningham LN, Racanielli A, Siconolfi SF, and Sholes JL. Validity of "generalized" equations for body composition analysis in male athletes. Med. Sci. Sports Exerc. 1985; 17:124-130.

24. Steinman AM and Kubilis PS. Survival at sea: The effects of protective clothing and survivor location on core and skin temperatures. U.S. Coast Guard Rept. No. CG-D-26-86. Nat. Tech. Info. Serv. Springfield, VA; 1986.

25. Webb P. Afterdrop of body temperature during rewarming: an alternative explanation. J. Appl Physiol. 1986; 60:385-390.

26. White JD, Butterfield AB, Greer KA, Schoem S, Johnson C, and Holloway RR. Comparison of rewarming by radiowave regional hyperthermia and warm humidified inhalation. Aviat. Space Environ. Med. 1984; 55:1103-1106.

27. Winer BJ. Statistical Principles in Experimental Design. New York: McGraw-Hill, 1962.

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